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Near-Miss Shock Response Analysis of an Encanistered Vertical Launch Antisubmarine Rocket Carrying a MK 54 Torpedo

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ABSTRACT

Described is a NASTRAN finite element near-miss shock response simulation of a Vertical Launch Antisubmarine Rocket (VLA) missile carrying a Mk 54 torpedo. The numerical simulation represents an encanistered Mk 54 VLA missile in a launcher cell subjected to "qualification level" shock. The finite element representation models the torpedo, airframe, rocket motor, canister, canister adaptor, and dog-down structure. Scaled acceleration time histories were enforced at the top of the canister and at the base of the canister adaptor. Vertical inputs were scaled from acceleration data recorded aboard USS Mobile Bay (CG 53) during the 1987 shock trials. Lateral inputs were scaled from acceleration data recorded aboard the standard floating shock platform (FSP) during the 1992 barge shock tests of an SM-2 Block IV missile. Shock inputs were applied to the finite element model (FEM) at canister support points. Missile loads were predicted and compared with VLA allowable loads. Shock response spectra (SRS) were predicted at critical missile locations and compared to those from the ship shock trials. Survivability of the Mk 54 VLA missile when subjected to these qualification level shock conditions aboard ship was predicted.

1. INTRODUCTION

The Space and Naval Warfare Systems Center (SPAWARSYSCEN) San Diego has recently performed a NASTRAN finite element near-miss shock response simulation of VLA missile carrying a proposed Mk 54 warshot configured torpedo. The numerical simulation represents an encanistered Mk 54 VLA missile in a launcher cell subjected to "qualification level" shock. The finite element representation consists of beam models of the torpedo, airframe, rocket motor, canister, canister adapter and dog-down structure. Scaled acceleration time histories were enforced at the top of the canister and the base of the canister adapter. Vertical inputs were scaled from acceleration data recorded aboard the USS Mobile Bay (CG 53) during shock trials conducted in 1987. Lateral inputs were scaled from acceleration data recorded aboard the standard floating shock platform during the 1992 shock tests of an SM-2 Block IV missile and Mk 21 canister. The Large Mass Method [1] was used to apply the shock inputs at the canister support points in the launcher to excite the encanistered VLA finite element model so that the response of the missile could be calculated. Missile loads were predicted and compared with Mk 54 VLA allowable loads. Acceleration shock response spectra were predicted at critical missile locations and compared to those from the CG 53 ship shock trials. Based on these comparisons, the survivability of the proposed Mk 54 VLA missile when subjected to the near-miss shipboard shock conditions was predicted.

2. VERTICAL LAUNCH ASROC AND VERTICAL LAUNCHING SYSTEM

The VLA is an intermediate-range anti-submarine warfare (ASW) missile launched from surface combatants equipped with the Mk 41 Vertical Launching System (VLS). The purpose of the VLA missile is to deliver a lightweight torpedo near a target submarine. Figure 1 depicts a diagram of an assembled Mk 54 VLA missile restrained inside a Mk 15 canister in a launcher cell. The VLA missile is composed of a nose cap, torpedo, air stabilizer, airframe, digital autopilot control (DAC), rocket motor, and thrust vector control (TVC). Note that the missile flight control devices of DAC and TVC and the air stabilizer, a parachute deployed to slow down the descending missile after its powered flight and ballistic glide prior to water entry, are not shown in Figure 1.

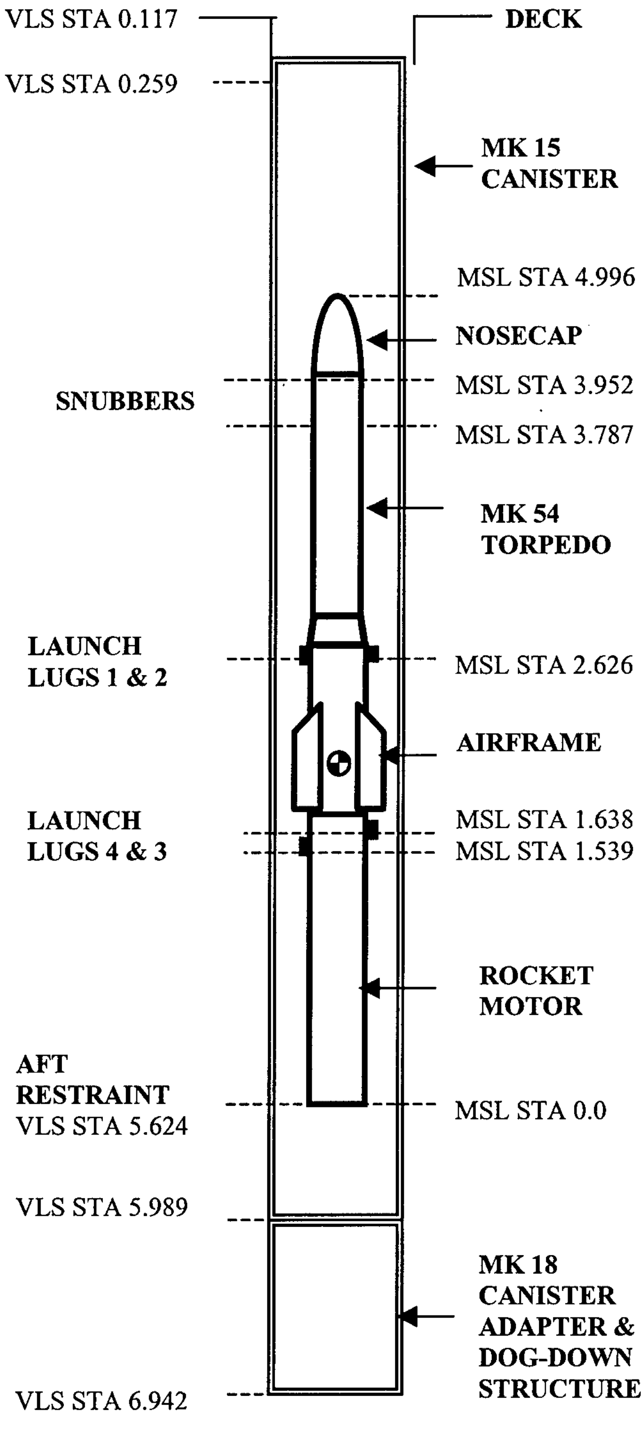

Figure 1. Encanistered Mk 54 VLA in a Launcher Cell

The Mk 15 canister serves as both a storage and shipping container for the VLA missile. The launch rails (not shown in Figure 1) are an integral part of the canister structure, and the canister itself is considered part of the VLS. The VLA missile is essentially "hard mounted" in the canister via two aft restraint studs and four shoes which engage the launch rails. The VLS canister also provides a set of retractable snubber pads to restrict lateral motion of the torpedo in the canister. During launch, the snubbers retract, and the missile exits the canister via the fly-through cover. Figure 1 defines the VLA missile and VLS axial coordinate systems and indicates the locations at which the canister mechanically constrains the missile. Note that the origin of the VLS stations (VLS STA) is located near the surface of the deck, while the origin of the missile stations (MSL STA) is located at the aft restraint of the VLA missile. SI units are used in this report, i.e., the units are based on the meter, kilogram, second, etc. Figure 1 also depicts Mk 18 canister adapter as it is configured in an individual VLS cell aboard ship.

The Mk 18 canister adapter is an open-ended steel weldment that serves as a conduit for rocket motor exhaust vented to the plenum. Enclosing the canister adapter is a frame structure known as the dog-down fixture. The dog-down fixture mechanically engages the bottom four corners of the Mk 15 canister. The "dogs" exert an axial compressive force or "preload" that promotes a gas-tight seal at the Mk 15/Mk 18 interface and at the Mk 18/plenum interface. The presence of the preload permits the transfer of moments between the Mk 15 canister and Mk 18 canister adapter. In the same way, moments can be transferred between the Mk 18 canister adapter and the plenum. The dog-down fixture also serves to restrain the vertical and rotational motion of the Mk 15 canister base. The top of the Mk 15 canister is free to slide vertically, but constrained laterally.

3. CG 53 SHOCK TRIALS AND DESIGN LEVEL COMPONENT TEST REQUIREMENTS

The USS Mobile Bay (CG 53) was subjected to a series of four underwater explosions in 1987. There were numerous sensors located on missiles, canisters and supporting structures throughout the forward and aft vertical launchers. The primary purpose of VLA participation in these tests was to demonstrate the ability of VLA to successfully survive the shock trials environment and to provide data for the determination of the "design level" near-miss shock requirements for VLA components.

"Design level" near-miss shock requirements for VLA missile components were established in the form of shock response spectra (SRS). These SRS appear in VLA weapon specifications for the nose cap, air stabilizer, digital autopilot control and thrust vector control. In applying the CG 53 shock trial results to component test requirements, it is important to note that the shock trials were not at "design level" and that the four shots were at different locations with respect to the ship. Reference [2] indicates that in determining the "design level" spectra, equal weight was given to all four shots. The data from each shot was linearly extrapolated to "design level". The shock spectra for the extrapolated responses for all four shots were then enveloped to produce the "design level" shock response spectra. This approach is believed to be conservative. The CG 53 "design level" SRS will be plotted alongside the SRS curves of the predicted shock response for the MK 54 VLA components to detect excessive motions in Section 10, "Predicted Mk 54 VLA Shock Response".

4. ENCANISTERED MISSILES SHOCK QUALIFICATION TEST (EMSQT)

In 1990 a VLS test fixture was installed on a standard floating shock platform at Aberdeen Proving Ground and subjected to a series of underwater explosions. These tests were conducted with Tomahawk and Standard missiles. VLA did not participate. The "barge" test data were analyzed and compared to that from the USS MOBILE BAY (CG 53) Shock Trial. Subsequently, NAVSEA, via Reference [3], established the Encanistered Missile Shock Qualification Test (EMSQT) program. EMSQT requires that VLS encanistered missiles be barge-tested with a charge standoff of 7.925 meters. This "qualification level" is based on 130% of the maximum CG 53 "design level" data. The 30% margin allows for experimental and analytical uncertainty, as well as variations in hull type and attack geometry. As of the date of this report, the VLA missile has not been "barge" tested.

In 1992, an instrumented SM-2 Block IV missile and Mk 21 canister were shock tested in the VLS test fixture aboard the FSP at Aberdeen. Acceleration records from this "barge" test form the basis for the lateral inputs in the athwartship and fore-and-aft directions to the present analysis.

5. MK 54 VLA "STICK" MODEL AND ENCANISTERED MK 54 VLA MISSILE FEM

In order to reduce the disk storage and computational time associated with dynamic simulations, dynamic finite element models are generally less detailed than those used for stress analysis. For this reason, dynamic analysis of VLA and associated VLS components is based on the simple beam representation depicted in Figure 2. This simple missile model is referred to as the VLA "stick" model. The VLA missile is represented by a series of elastic beam elements connected end-to-end along the missile axis. Beam element section properties are obtained from the appropriate technical data package. For example, a beam element representing the torpedo fuel tank would have a cross-sectional area, area moment-of-inertia and elastic modulus derived from the fuel tank technical drawing. In addition to beam elements, mass elements are assigned at specific locations to represent the mass of missile components. Spring elements are used to model structural stiffness not amenable to beam element representation. In particular, joints between missile subsections are represented in the FEM by discrete spring elements.

The proposed Mk 54 torpedo is approximately 0.178 meter longer and about 40.8 kilos heavier than the Mk 46 Mod 5. The Mk 54 torpedo FEM was generated by modifying the existing Mk 46 Mod 5 torpedo FEM as described in Reference [4]. The Mk 54 VLA missile FEM was generated by joining the Mk 54 torpedo FEM to the same airframe and rocket motor models used in the existing Mk 46 Mod 5 VLA missile FEM reported in Reference [5].

The Mk 54 VLA missile FEM was joined to the Mk 15 canister FEM [6] generated by United Defense Limited Partnership (UDLP) to form the Mk 54 VLA encanistered missile FEM. An encanistered VLA missile is referred to

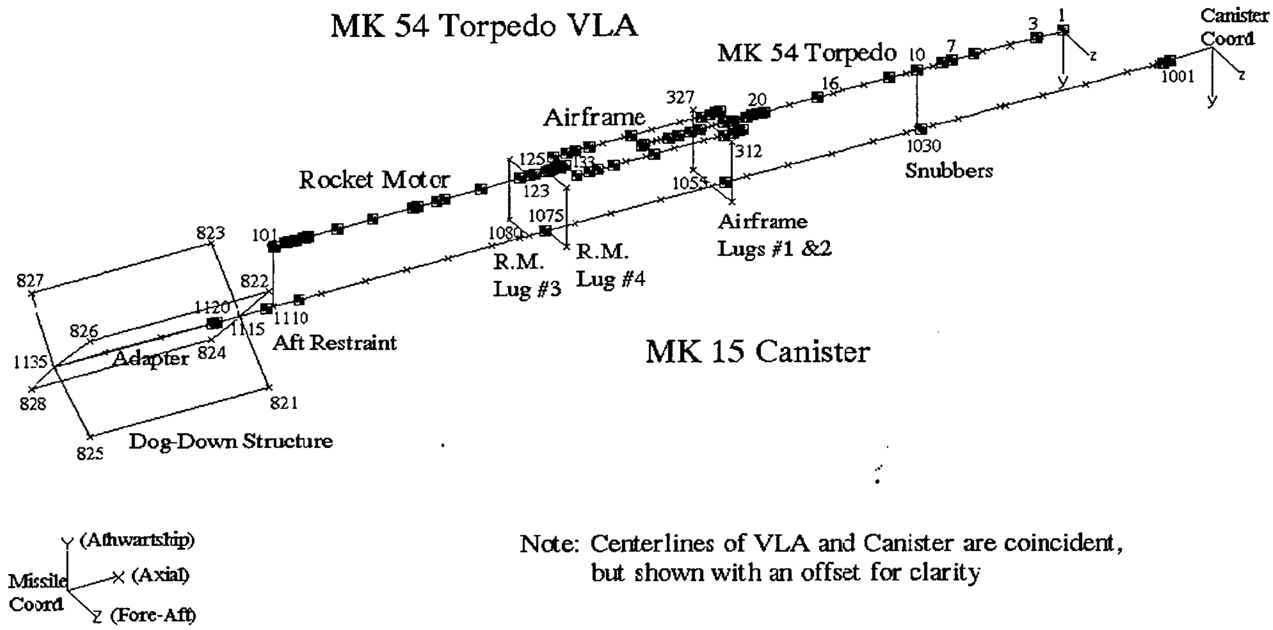

Figure 2. Finite Element Model of Mk 54 VLA Encanistered in a Mk 15 Canister Attached to a Mk 18 Canister Adapter and Dow-down Structure

as an All-Up-Round (AUR) as depicted in Figure 1. The Mk 15 canister mechanically constrains the VLA missile at the aft restraint, the rocket motor launch lugs, the airframe launch lugs and the snubbers. These mechanical devices are represented in the encanistered missile FEM by discrete spring elements. The missile/canister mechanical interfaces remain unchanged from the Mk 46 to the Mk 54 missile configuration. Table 1 presents the interface stiffness values used in the FEM. These values are established by Reference [7], the VLS/VLA Mechanical Interface Document (MICD). The tabulated values of interface stiffness at the launch lugs are a combination of lug stiffness and rail stiffness. Opposing launch lugs cannot simultaneously restrain fore-and-aft (z-axis) motion. Only one of the opposing lugs restrains z-displacements at any instant in time. For this reason, fore/aft stiffness values are assigned to lugs 1 and 4 only. Thus, fore-and-aft reactions cannot be computed at lugs 2 and 3 using the FEM; however, it is reasonable to assume that these lugs will develop reactions comparable to their opposing companions. The X, Y and Z coordinates referenced in Table 1 refer to the FEM missile coordinates shown in Figure 2, which is identical to the MICD missile coordinate system.

Table 1. FEM Stiffness at Canister/Missile Interface

Interface	Translational Stiffness (10^6 kgf/m)			Rotational Stiffness (10^3 m-kgf/rad)		
	Axial X	Athwart Y	Fore/Aft Z	About X	About Y	About Z
Snubbers	0	0.8090	3.6788	0	0	0
Lug #1	0	0.5307	0.8027	0	0	0
Lug #2	0	0.5307	**Note 1**	0	0	0
Lug #3	0	0.8101	**Note 1**	0	0	0
Lug #4	0	1.1022	1.7533	0	0	0
TVC/Aft Restraint	26.7875	10.2685	43.2171	610.6	168.2	839.9

1. The Fore/Aft stiffness of lugs 2 and 3 are accounted for by the Fore/Aft spring elements at lugs 1 and 4.

6. FEM OF ALL-UP-ROUND WITH MK 18 ADAPTER AND DOG-DOWN FIXTURE

UDLP developed a Mk 18 canister adapter model comprised of four beam elements connected in series along the launch cell vertical axis. The canister adapter model stiffness is based on the structure's material and section properties obtained from the appropriate technical drawings. As indicated by Reference [6], the contribution of the corrugated shell is difficult to gauge without benefit of testing. In short, it is not clear what section properties should be assigned to the FEM beam elements. To date, the canister adapter model's mechanical behavior has not been verified by testing. The Mk 18 canister adapter FEM represents the structure's weight as 279.5 kilos. The top of the Mk 18 canister adapter model interfaces with the base of the Mk 15 canister model in such a way as to permit the transfer of shear, bearing and torsion; but no moments. In reality, moments can be transferred, as long as the clamping force joining the canister and adapter is not exceeded. Numerical shock simulations indicate that very little moment is transferred across this joint whether it is modeled as "hinged" or continuous.

The dog-down fixture, which encloses the Mk 18 canister adapter, was modeled by UDLP with four beam elements to represent the fixture's four corner posts. Spring elements between the base of the canister model and base of the adapter model represent the dog-down fixture's horizontal shear stiffness. A special rigid element* facilitates the transfer of moments from the base of the Mk 15 canister to the top of the dog-down fixture.

An identical element permits the transfer of moments from the base of the Mk 18 canister adapter to the bottom of the dog-down fixture. Only axial displacement of the four corner posts is permitted. Axial forces in opposing corner posts act as a couple to generate moments in the dog-down fixture. In contrast to the actual VLS shipboard installation, this model configuration permits rotation of the launcher cell base. When rotational constraints are enforced at the base of the dog-down fixture, computed forces and moments change by up to 30% at some missile locations. In contrast to the UDLP approach, the SPAWARSYSCEN shock analysis will rotationally constrain the base of the FEM. The mechanical behavior of the dog-down model has not been verified by measurement.

The NASTRAN FEM of the encanistered Mk 54 version of VLA including canister adapter and dog-down structure is presented in Figure 2. The entire model is comprised of 322 elements and has a numerical mass of 1745.5 kilos. For the purposes of transient shock analysis, the external constraints are the enforced translational motions at each end of the model, plus the rotational restraints at the base. The top of the Mk 15 canister is unrestrained in the axial direction. This model forms the basis for the numerical near-miss shock analysis of the Mk 54 VLA missile.

7. TRANSIENT RESPONSE ANALYSIS METHOD

The purpose of a transient response analysis is to compute the behavior of a structure subjected to time-varying excitation. Given the excitation at each instant in time, the time-varying response of the structure can be predicted. Two different numerical methods are available for transient response analysis: direct integration and modal superposition. The direct integration method numerically integrates the coupled equations of motion. The modal superposition method sums the individual modal responses of the uncoupled equations of motion. For linear models, the modal superposition method is usually more efficient and generally preferred over direct integration. SPAWARSYSCEN engineers employed the modal superposition method to predict the response of the Mk 54 variant of the VLA missile to near-miss shipboard shock.

The modal superposition method requires the application of modal damping. By this approach, individual modes can be assigned individual values of damping. According to Reference [8], measured damping values for the first six modes of the encanistered Mk 46 VLA, range from roughly 1% to 13% of critical damping (depending on the mode of vibration and level of excitation). For high excitation levels (expected during near-miss shipboard shock) the damping ratios range from 6% to 13%. For the purposes of the present analysis, finite element solutions were computed for both 2.5% and 10% of critical damping. The actual missile response will most likely fall between these two solutions.

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* NASTRAN provides a "rigid body element", designated RBE2, having one "master" node and multiple "slave" nodes. The user defines the active degrees-of-freedom (DOF) at these nodes. In the case of the dog-down FEM, UDLP employed such elements at each end of the canister adapter. The end adapter nodes were designated as "masters" with the corner post nodes as "slaves". UDLP activated all six DOF at the master nodes, but only the axial DOF at the slave nodes.

8. EXCITATION

As indicated Section 4, NAVSEA established the encanistered missile shock "qualification level" as 130% of the maximum CG 53 "design level" shock (equivalent to a barge test with a charge standoff of 7.925 meters). The current NAVSEA policy is that all encanistered missiles be shock qualified on the barge. Logic would dictate that the present near-miss shock simulation should therefore be based on barge shock inputs. In fact, this was the original plan. It was determined, however, that when all data is scaled to "qualification level", the barge peak vertical acceleration (at the plenum) is more than twice that of the CG 53 shock trials. More importantly, the maximum predicted VLA missile response to vertical shock is five times greater for the barge data than for the CG 53 data. UDLP and SPAWARSYCEN concluded that the barge vertical shock for a 7.925-meter standoff is unrealistically severe for shock qualification of the VLA missile. UDLP and SPAWARSYCEN believe that the most appropriate input shock consists of the CG 53 vertical component and the barge lateral components. Thus, the excitation used in the present analysis consists of the CG 53 vertical shock component and the barge lateral shock components all scaled to "qualification level".

The Mk 46 variant of the VLA missile was shock tested on board the USS MOBILE BAY (CG 53) in the summer of 1987 along with the Tomahawk and SM-2 Block II missiles. Nearly 300 sensors were installed in the VLS magazines to measure the system's mechanical response to near-miss shock. According to UDLP, measured motion at the bottom of a launcher cell is dependent on cell location and independent of the weapon type in the cell. The "worst case" vertical shock component was identified at cell 4-4 of the aft launcher during shot 3. This vertical shock component is used as the vertical input in the current finite element analysis. Lateral inputs were taken from acceleration data recorded aboard the standard floating shock platform (FSP) during the 1992 shock tests of an SM-2 Block IV missile and Mk 21 canister. Table 2 lists the accelerometers that form the basis for the input data set in the present analysis. In addition to sensor number, Table 2 specifies sensor locations and directions.

Table 2. Enforced Motion Data Set[2]

Sensor Label	Test	Direction	Model Location	
			VLS Coord. (m)	Description
6A3011F	Barge[1]	Fore-aft	0.260	Top of Canister
6A3010A	Barge[1]	Athwartships	0.260	Top of Canister
A7360V	CG 53*	Vertical	6.941	Base of canister Adapter
6A3004A	Barge[1]	Athwartships	6.941	Base of Canister Adapter
6A3005F	Barge[1]	Fore-aft	6.941	Base of Canister Adapter

* 1987 CG-53 Ship Shock Trials, Cell 4-4, Aft launcher.
1. 1992 Floating Shock Platform test of SM-2 Block IV.
2. Tabulated acceleration records must be scaled to "qualification level".

The shock intensity associated with ship shock trials does not represent "design level" shock. The CG 53 vertical acceleration record listed in Table 2 must be scaled by a shock factor to obtain design-level acceleration. Furthermore, encanistered missile shock qualification is based on 130% of the CG 53 design-level; thus, record A7360V must be scaled by a factor equals to 1.30 times the shock factor to produce the "qualification level" shock required in the present near-miss ship shock analysis. Regarding the lateral inputs, the actual charge standoff during the 1992 barge test was 9.754 meters. The lateral acceleration records in Table 2 must be scaled by a factor approximately equal to the distance ratio to produce the "qualification level" shock equivalent to a charge at 7.925 meters. Plots of the "qualification level" acceleration time histories can be found in Figures 3 and 4. Each time history is accompanied by its associated acceleration shock response spectra.

9. FEM NEAR-MISS SHOCK ANALYSIS BOUNDARY CONDITIONS

Scaled acceleration time histories from Table 2 were applied as enforced motions at each end of the VLS/VLA finite element model. The top of the model is free to move axially. Although two different plenum boundary conditions were investigated, only results for the rotationally constrained base are presented in this report. No other external boundary conditions constrain the model.

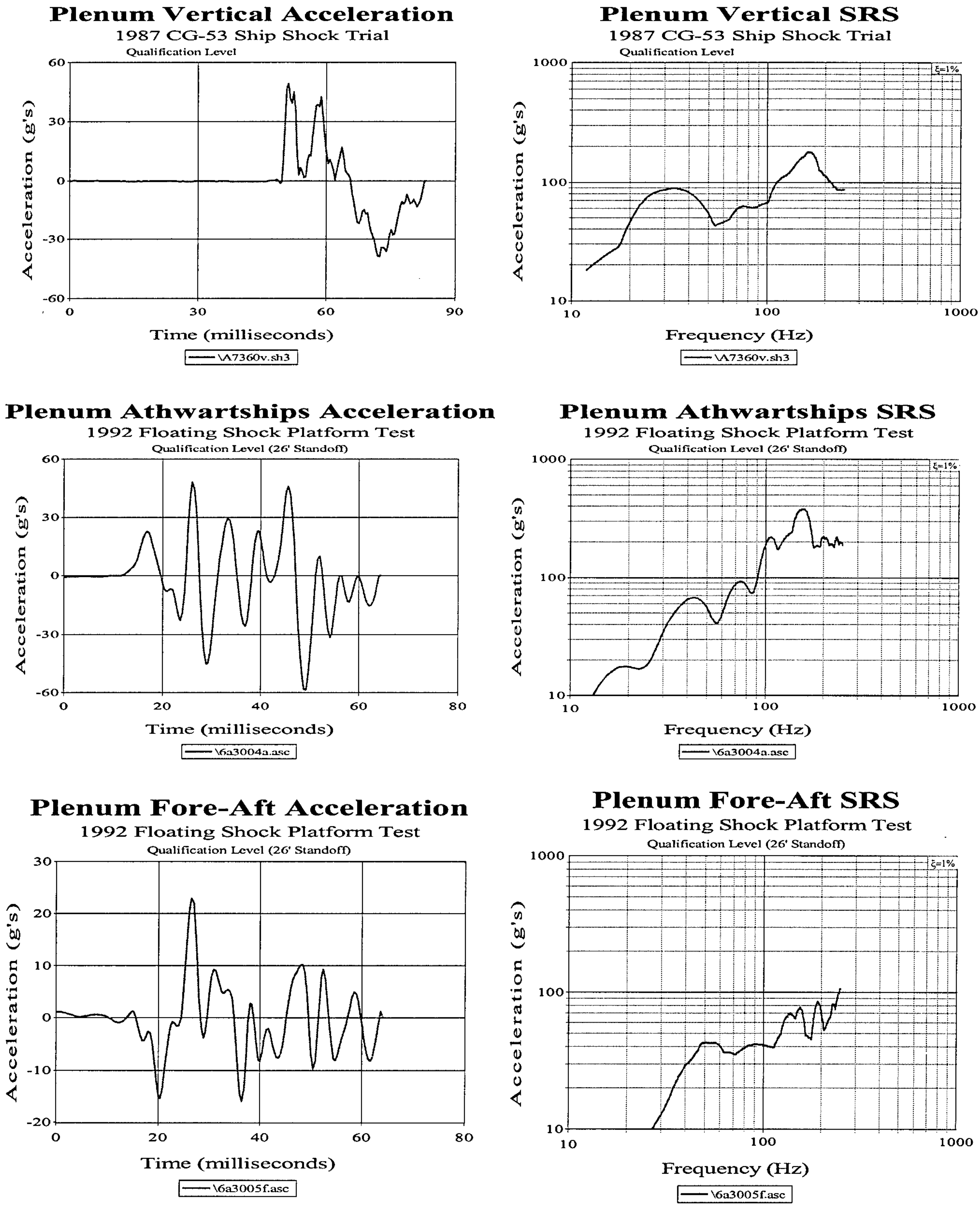


Figure 3. Enforced Motion and SRS at the Base of Mk 18 Canister Adapter

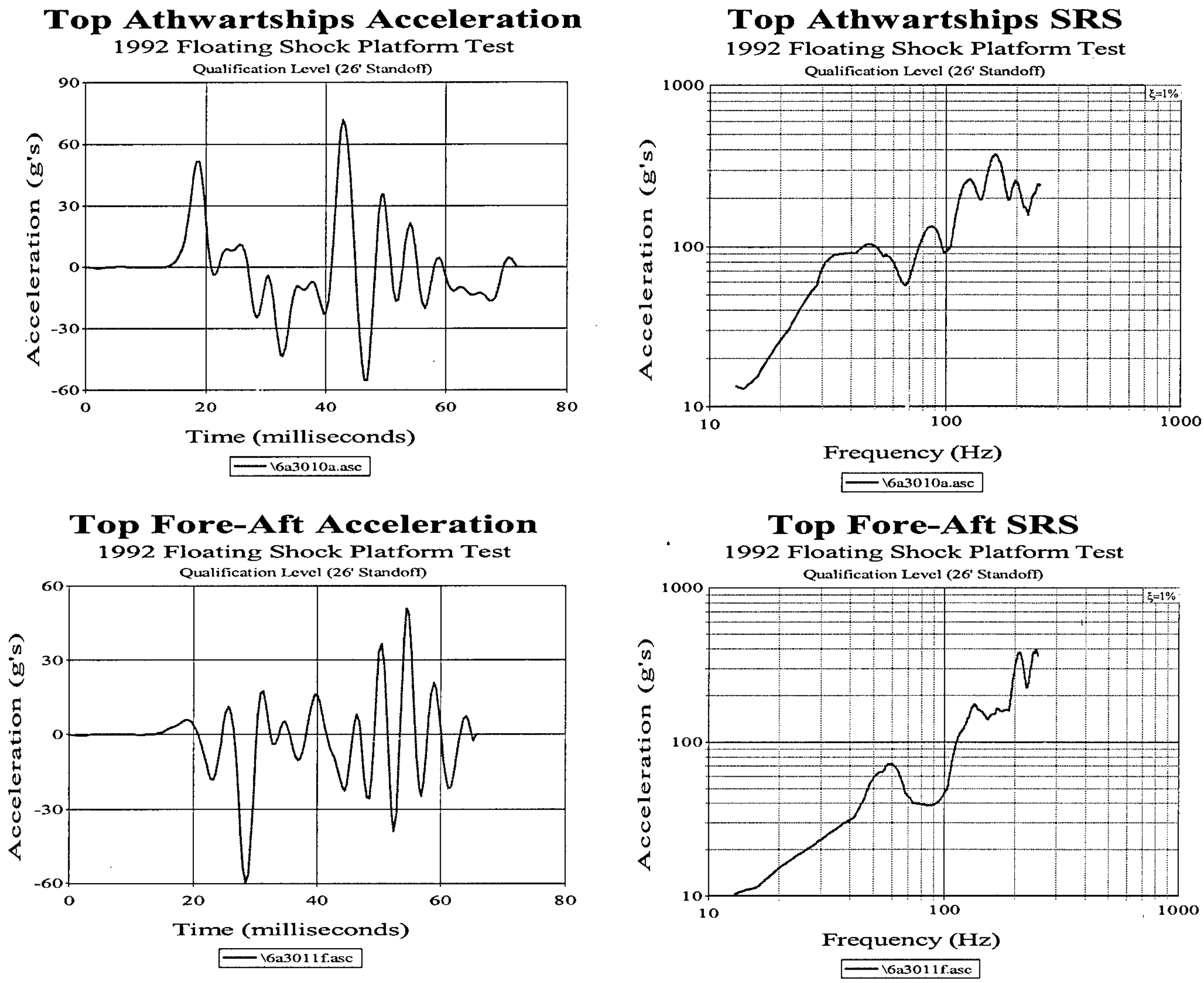


Figure 4. Enforced Motion and SRS at Top of Mk 15 Canister

10. PREDICTED MK 54 VLA SHOCK RESPONSE

The VLS/VLA FEM response was calculated at each time step during the period of enforced motion (plus an additional 5 milliseconds) for a total analysis period of 0 to 85 milliseconds. Figures 5 through 8 plot the predicted Mk 54 VLA acceleration time histories at the sonar electronics housing, air stabilizer, digital autopilot control (DAC), and thrust vector control (TVC).

Predictions for the axial and athwartships directions for 10% modal damping case are presented. Fore-aft motions are not presented because they are less severe than that of the athwartship direction. The shock response spectra associated with the predicted acceleration time histories were plotted against the CG 53 "Design Level" Requirements. 1% of critical damping was used in the calculation of the shock response spectra.

As can be seen from Figures 5 through 8, the response motions at the sonar, air stabilizer, DAC and TVC are below the CG 53 Design Level Requirement SRS for response frequencies below 100 Hz. Above 100 Hz, the CG 53 Design Level SRS is exceeded at multiple missile locations. This is due to the higher frequency content included in the enforced motions (depicted in Figures 3 and 4), but not in the CG 53 Design Level SRS that are based on a different launcer cell and established prior to the EMQST program.

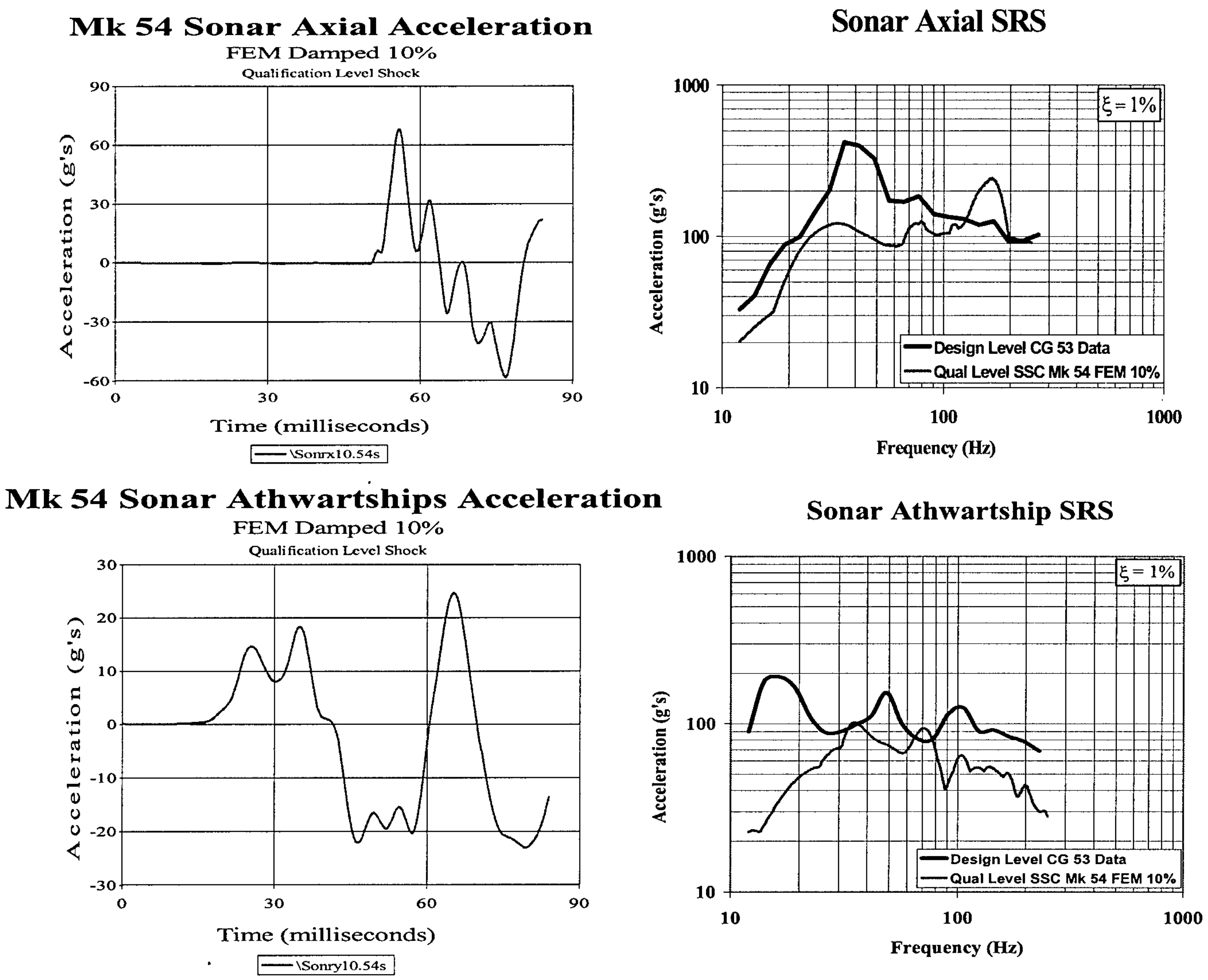
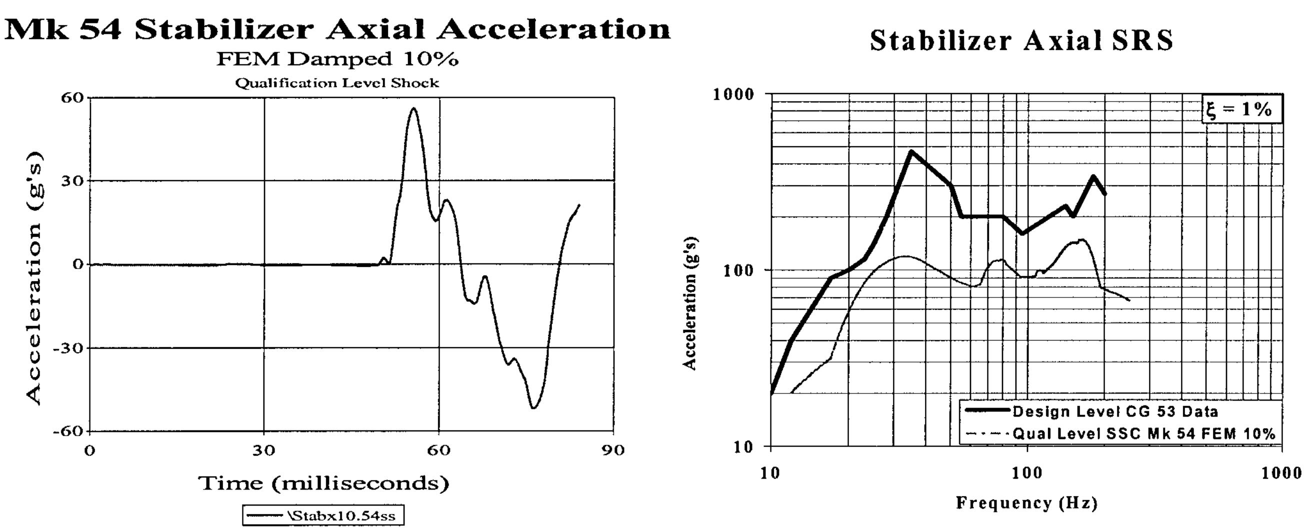


Figure 5. Predicted Axial and Athwarship Accelerations and SRS at Sonar



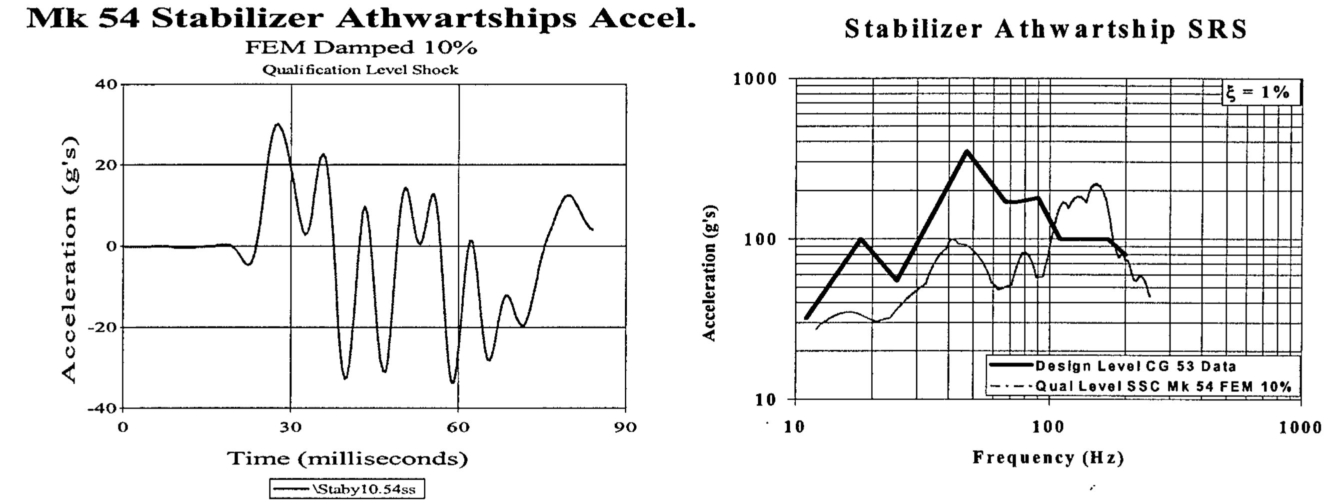


Figure 6. Predicted Axial and Athwartship Accelerations and SRS at Stabilizer

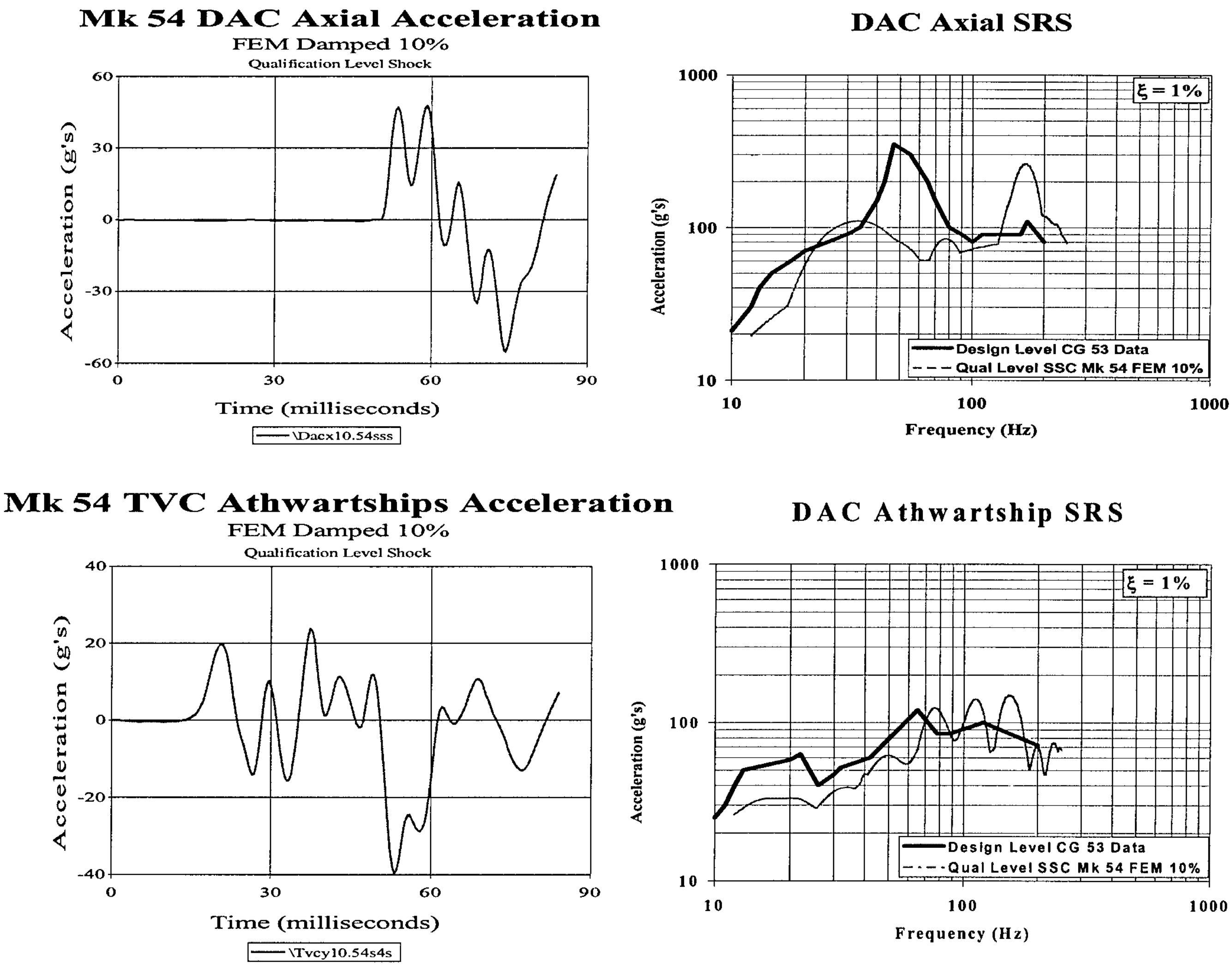


Figure 7. Predicted Axial and Athwartship Accelerations and SRS at DAC

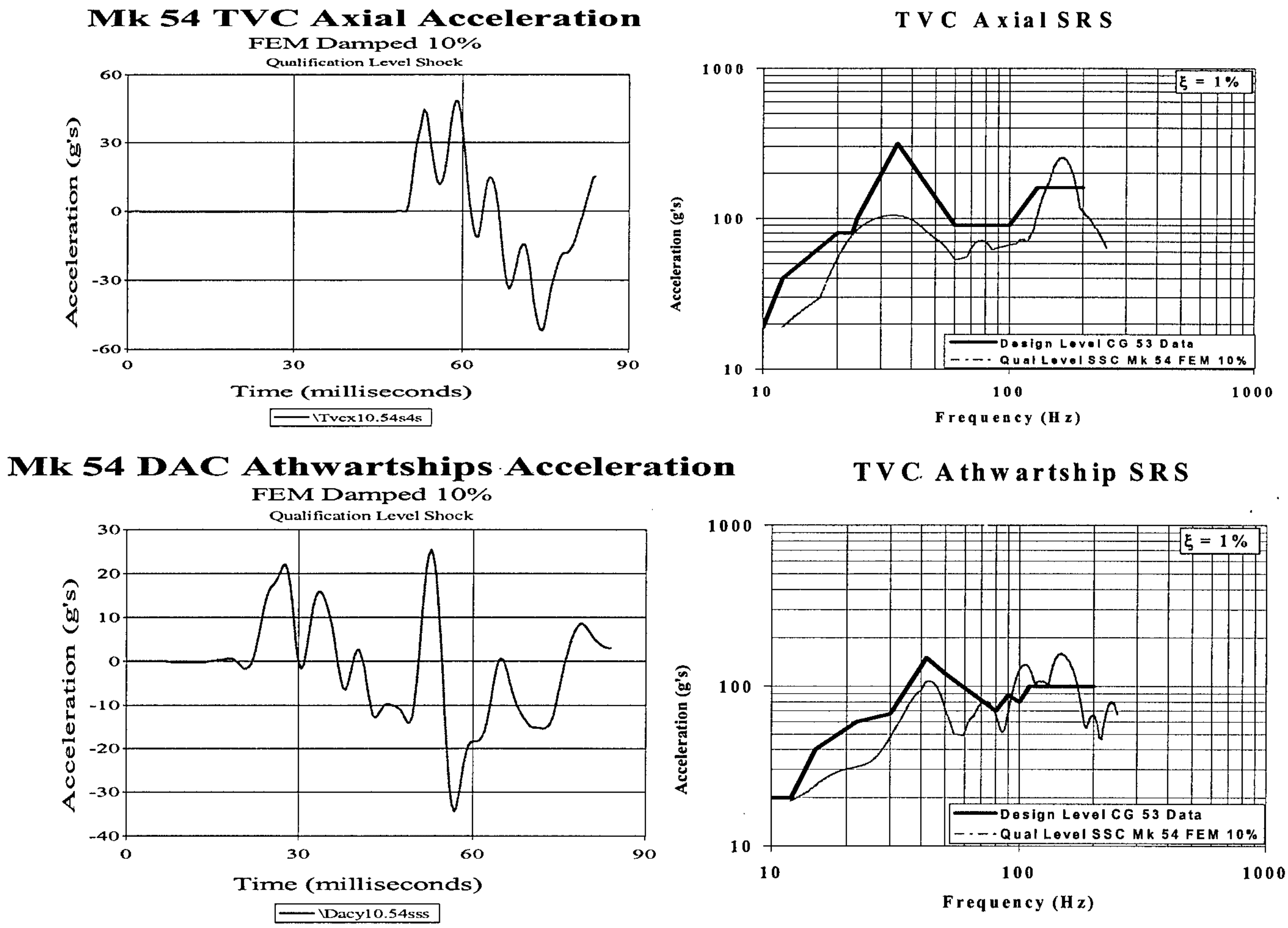


Figure 8. Predicted Axial and Athwartship Accelerations and SRS at TVC

11. FEM NEAR-MISS SHOCK ANALYSIS PREDICTED MAXIMUM LOADS

Force and displacement time histories were computed at key missile locations. Peak axial, shear and bending loads are presented in Table 3. The missile motion was predicted for both 2.5% and 10% of critical damping to assess the influence of damping on the structure's response. Consequently, a range of predicted values appears in Table 3.

Table 3. Maximum Response Loads of an Encanistered VLA Missile to Qualification Level Near-Miss Shock

Missile Location	Axial Force (F_X kgf)	Athwart Shear (F_Y kgf)	Fore-Aft Shear (F_Z kgf)	Moment about Y (M_Y m-kgf)	Moment about Z (M_Z m-kgf)
Sonar	4536 – 5988	1588 – 2722	1588 – 2404	98 – 183	98 – 203
Warhead	5808 – 7620	1814 – 2722	1905 – 2676	644 – 1049	703 – 1248
Snubbers	N/A	4309 – 4944	5307 – 6486	1369 – 1966	1295 – 2049
Fuel Tank	11113 – 14561	1633 – 1905	2268 – 2903	1097 – 2310	1711 – 2512
AF Lug #2	N/A	1270 – 1588	Unknown	N/A	N/A
AF Lug #1	N/A	1315 – 1633	1452 – 2948	N/A	N/A
Afterbody	14606 – 19051	1497 – 1951	907 – 2223	1017 – 2038	1553 – 1989
RM/AF Joint	19686 – 24903	1452 – 2041	1452 – 3447	926 – 1307	2308 – 3164
RM Lug #4	N/A	1814 – 3039	1588 – 2404	N/A	N/A
RM Lug #3	N/A	1452 – 2449	Unknown	N/A	N/A
RM/TVC Joint	30119 – 31026	6169 – 9435	2948 – 4309	463 – 649	948 – 1513
Aft Restraint	31480 – 32977	7031 – 10660	3493 – 4990	183 – 278	977 – 1578

The Margin of Safety (MS) is defined as the ratio of the allowable load over the predicted working load minus 1.0. The allowable loads come from three different sources. The source for allowable loads at the missile constraint points is the MICD, Reference [7]. The source for Mk 54 torpedo allowable loads is Reference [9]. The source for all other missile allowable loads is Reference [10].

The Environmental and Structural Design Requirements for VLA, Reference [11], specifies that for shipboard shock, allowable loads should be based on ultimate strength with a factor-of-safety (FS) of 1.00; except in the case of local load introduction, where FS should equal 1.25. These guidelines have been followed with respect to the missile and missile constraints. An exception has been made in the case of the torpedo. The allowable torpedo loads are based primarily on yield strength with an FS = 1.00. This is because yielding of the torpedo joints may compromise the structure's watertight integrity. Consequently, the allowable loads used to calculate MS of the maximum predicted loads in Tables 3 is not based on a single safety factor or material condition.

12. SUMMARIES AND CONCLUSION

Tables 3 indicates that all the VLA missile critical locations have positive safety margins, except the following:

(1) The shear force in the Z-direction at AF Lug #1 (2948 kgf) has a slight negative MS of –0.046 when compared to the allowable load. This result is predicted for the "worst case" damping ratio of 2.5%. Since the true damping ratio is closer to 10%, the safety margin is considered positive.

(2) The bending moment about the Y-axis at the Fuel Tank (2310 m-kgf) has a slight negative MS of –0.025. As described in the previous section, the torpedo "allowables" are conservatively based on the yield strength of the material rather than the higher ultimate strength. Furthermore, this negative safety margin is predicted for the "worst case" damping ratio of 2.5%. Since the true damping ratio is closer to 10%, the safety margin is considered positive.

(3) The bending moment about the Z-axis at the Fuel Tank (2512 m-kgf) also has a negative MS (-0.103). Again, this result is predicted for the "worst case" damping ratio of 2.5%. Since the true damping ratio is closer to 10%, the safety margin is considered positive.

It can be concluded that the current analysis indicates that the Mk 54 VLA will survive near-miss shipboard shock.

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